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MEASUREMENT OF THE ENERGY OF FAST IONS IN A POWERFUL PULSED DISCHARGE

/Following is a translation of an article by B. G. Brezhnev in the Russian-language periodical Izvestiya Akademii Nauk SSSR -- Energetika i Avtomatika (Bulletin of the Academy of Sciences USSR -- Power Engineering and Automation), No 2, Moscow, 1960, pages 54-58./

The production and study of high-temperature plasma in straight discharge tubes led to a more or less clear idea of the rate of growth and distribution of the discharge current, the character of the change in the discharge voltage, the detachment of the plasma from the walls of the discharge tube and the degree of its compression, and the distribution of the proper magnetic and electric fields and other properties of such plasma /1, 2/. However the nature of the hard radiation discovered in the first years of the study of high-temperature plasma still remains unknown in spite of a fairly large number of works by Soviet and foreign authors.

It is well known that a pulsed discharge in deuterium at low pressure is accompanied by x-ray and neutron radiation /3, 4/. The neutron yield is observed in a very short range of time which coincides with the time of maximum compression of the plasma. The plasma is very unstable when in a state of maximum compression. It is probable that the instability of the plasma leads to the formation of strong electric fields. In this case, the deuterons in the plasma are accelerated when they pass through strong electric fields and their velocity may be several times greater than that which they would have acquired from the application of the initial potential difference to the discharge tube /5/.

Up to the present time only indirect evaluations of the velocities of deuterons are known which were obtained from studying the spatial distribution of the neutrons and their energies /6, 7/ and which show that the plasma may contain deuterons with energies up to 200 Kev. However, the direct measurement of the velocities of fast neutrons is of material interest.

In order to measure the energies of fast ions it was necessary to select a method which would permit measuring the energy over a wide range of time of a single powerful pulsed discharge.

Use of the method of the Thomson parabola /8/ in this work permitted measuring the velocity of the ions in wide limits and determining the value of e/M with sufficient reliability. Photographic

registration of charged particles, the use of a permanent magnet for producing the magnetic field and dry elements for obtaining the electric field wholly excluded the effect of powerful electromagnetic induction when measuring the energies of the ions.

Description of the Apparatus and Methods. The apparatus was a cylindrical porcelain tube $l = 80$ centimeters and $d_{vn} = 17.2$ centimeters, closed at the ends by metal flanges (Figure 1). The tube was pumped out through the cathode flange to a high vacuum ($\sim 2 \times 10^{-6}$ millimeters of mercury) by means of oil diffusion and initial vacuum pumps. This flange was connected with a cylindrical copper casing which contained the porcelain tube. This copper casing was connected with the ground plates of nine capacitors connected in parallel with a total capacitance of 24.3 microfarads and served as the return conductor for the discharge current. The battery of capacitors was charged from a rectifier with a grounded minus of up to 40 kilovolts and discharged with an igniter between the flanges inside the porcelain tube filled with pure deuterium. After passing through a palladium filter, the deuterons filled a measured volume which was connected with the tube before the beginning of the discharge. The tube was pumped out to a high vacuum and aged by repeated discharges up to the point of obtaining a sufficiently high production of neutrons before each experiment.

An aperture with a diameter of 15 millimeters was made in the cathode along the axis of the tube for extraction of the beam of charged particles. The end of a connecting metal tube from the special chamber was inserted into this aperture against a seal. The tube contained two diaphragms with circular apertures with diameters of 1 millimeter and 0.5 millimeter. The first diaphragm was closed by a high-speed electromagnetic valve and could be opened in 0.01 second before the beginning of the discharge, automatically switching on the device for igniting the discharge. After passing through the diaphragms of the connecting tube, the beam of charged particles from the discharge tube entered a flat box (4 x 4 x 1.8 centimeters) made of red copper placed between the poles of a permanent magnet. Two parallel copper plates (4 x 4 centimeters) were fastened to insulators inside the box and an electric field from a battery of dry elements was set up between them. Then the box was connected by means of a metal bell with the flat part of the chamber in which there was a plateholder with a 9 x 12 centimeter photographic plate /Type MR produced by the NIKFI (Nauchno-issledovatel'skiy kinofoto institut -- Scientific Research Institute for Motion Pictures and Photography/. The plateholder was fastened to a piston in the upper part of the chamber and, after the system was pumped out to a high vacuum prior to the discharge, was lowered into the lower part of the chamber while the cover of the plateholder remained above. The entire system consisting of the chamber, bell, box, and connecting tube with the diaphragms were made of metal, light-tight, and were pumped out continually to a high vacuum by means of separate pumps.

The ions from the plasma passed through the apertures in the cathode and the diaphragms, and entered the parallel magnetic and electric fields which acted upon the ions to change their paths in such a way that when the ions struck the photographic plate located at a distance of 10 centimeters from the center of the magnetic field they left parabolic streaks on the film. Each parabola corresponded to a single value of e/M while a definite velocity of an ion corresponded to each point on a parabola. The center of the plate was blackened in the form of a circle with a diameter of 4 millimeters where it was struck by a straight ray of light, fast neutral particles from charge exchange, fast ions and ions with large masses which were scarcely deviated from their initial direction of motion by the given magnetic and electric fields.

If we place the origin of the coordinates at the center of this spot, then, knowing the constants of the device (z, l), the intensities of the electric (E) and magnetic (H) fields, and measuring the coordinates (x, y) of any point of the parabola on the photographic plate, we can use the equation

$$y^2 = zle \frac{H^2}{EM} x \tag{1}$$

to find the value of e/M and the equations

$$x = zl \frac{eE}{Mv^2}, \quad y = zl \frac{eH}{Mv} \tag{1a}$$

to determine v -- the velocity of the ion.

The accuracy of the method of parabolas is not very high, but it is the most suitable for the simultaneous measurement of the energies of ions from several kilovolts to hundreds of kilovolts for 8 microseconds in a powerful pulsed discharge.

Every pulsed discharge was made with a gas pressure of 0.02-0.03 millimeters of mercury, a discharge voltage of 40 kilovolts, and a maximum discharge current of 1.5-2×10^5 amperes.

The time of exposure of the photographic plate for one pulsed discharge did not exceed several microseconds (on the order of the first half period, equal to 8 microseconds). When working with deuterium, the photographic plates were exposed in the presence of neutron radiation (with an average of up to 10^8 neutrons per pulse).

Results of the Measurements. Measurements of the velocities of the deuterons flying from the plasma perpendicular to the axis of the discharge showed that scarcely noticeable traces of parabolas were obtained with exposing photographic plates for 80-100 pulses. In this case the stream of ions was very small.

The stream of particles was markedly larger in experiments with beams of charged particles flying along the axis of the discharge and

passing through the aperture in the cathode. Weakly noticeable traces of parabolas were obtained on photographic plates after one pulsed discharge. Exposure for 3-5 pulses yielded parabolas with definite dark traces. When all the discharge parameters were held constant, the results of the measurements showed a wide dispersion. Maximum energies of deuterons were more frequently obtained within limits of 80-170 Kev and more rarely in the range of 170-200 Kev.

Two photographs obtained on one plate with the same discharge conditions in deuterium are shown in Figure 2. The upper left parabolas are: D^+ (strong blackening) and H^+ (weak blackening) and the right lower parabola is D^- with the same direction of the magnetic field. The maximum energy D^+ is equal to 184 Kev and D^- is 50 Kev. The upper right parabolas are: D^+ (strong blackening) and H^+ (weak blackening) and the left lower parabola is D^- when the magnetic field is in the other direction. The maximum energy of D^+ is 53 Kev while D^- is 40 Kev.

A photograph of D^+ and H^+ parabolas obtained from one pulsed discharge is shown in Figure 3.

Parabolas obtained with 12 pulsed discharges in hydrogen are shown in Figure 4. The parabola of H^+ ions is the lower one on the left and its maximum energies are equal to 200 Kev; the parabola of H^- ions is the upper one on the right.

When the exposures were lengthened (25 pulses or more), D_2^+ and D_2^-, also O^+, N^+, O^- parabolas accompanied by parabolas of ions from the materials of the electrodes and walls of the tube appeared in addition to the D^+ and D^- parabolas.

By changing the polarity of the charge on the capacitors it was possible to analyze the beams of charged particles which passed through the aperture to the anode. In this case no traces of parabolas were discovered on photographic plates exposed for 50 pulses.

Discussion of Results. The method of parabolas used to analyze beams of fast ions showed that the fast ions in the plasma produced by a powerful pulsed discharge in deuterium and hydrogen had a continuous spectrum with velocities ranging from 4 to 200 Kev. The probability that there were ions with energies below 4 Kev is not excluded, but the emulsion in the photographic places was not sensitive enough to register them. On the other hand, when one measured the blackening by a microphotometer in the direction of maximum energies, there was no sharp boundary and the blackening decreased slowly up to the central spot on the plate. Therefore one can believe that there were ions with energies exceeding 200 Kev in the plasma but that they were very few. It was possible to observe spots with great blackening visually and especially with microphotometry of the parabolas. The presence of these spots indicated a far from monotonous trend in the curve of the distribution of energies in the region of great energies.

The mechanism of the formation of fast negative ions is probably connected with the charge-exchange of fast positive ions, that is, with the appearance of fast neutral particles with subsequent

capture of electrons. In this case the direction of the velocities of the fast particles is scarcely changed. The maximum velocities of the negative ions are less than the maximum velocities of the positive ions on the same plate. The direction of the velocity of the negative ions coincides with the direction of the velocity of the positive ions, therefore they fly to the cathode, losing part of their energy in the retarding field.

The presence of deuterons with energies five times those of the discharge voltage indicates the appearance of accelerating processes in the discharge. Instability in a compressed plasma column can cause the formation of strong electric fields whose direction coincides with the direction of the principal field set up by the discharge voltage. In fact, experiments with changing the polarity of the capacitors, that is, with a change in the fast ions passing through the anode showed that fast ions appear only during the first half-period of the discharge current and the direction of the fields in which the ions are accelerated to great energies coincides with the field of the initial discharge voltage. The stream of fast ions is directed along the z-axis of the discharge tube toward the cathode with only insignificant scattering toward the walls. There are good grounds for believing that there should also be a stream of fast electrons accelerated in the same fields which are moving along the z-axis toward the anode.

Thus, neutron radiation during discharge in deuterium, at low pressure in straight tubes, is caused chiefly by accelerating processes in the plasma filament which accelerate deuterons up to 200 Kev.

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FIGURE APPENDIX

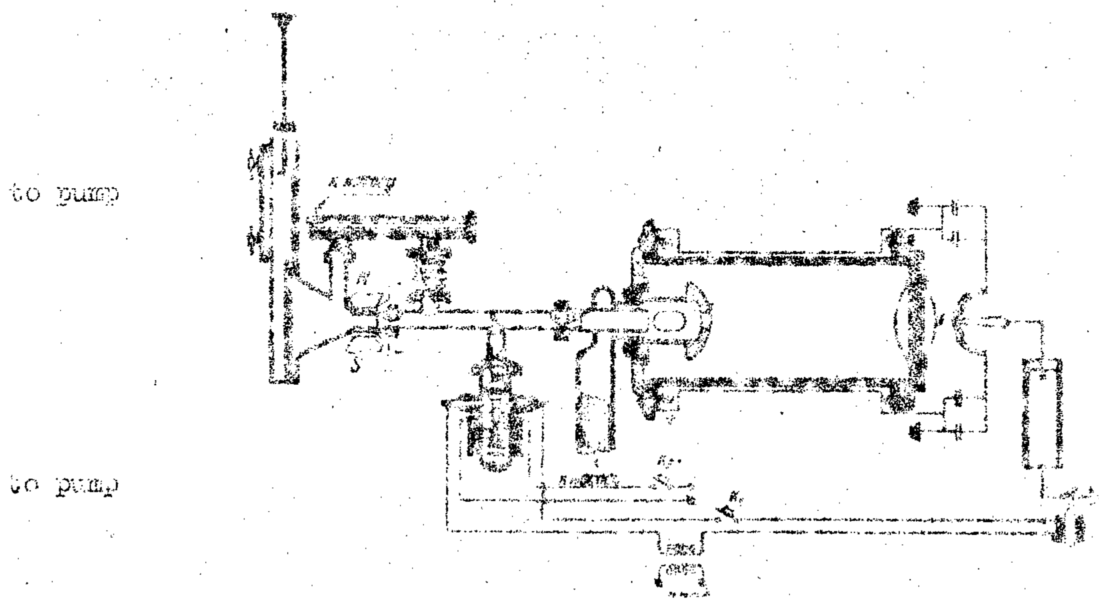

Figure 1. Diagram of the apparatus

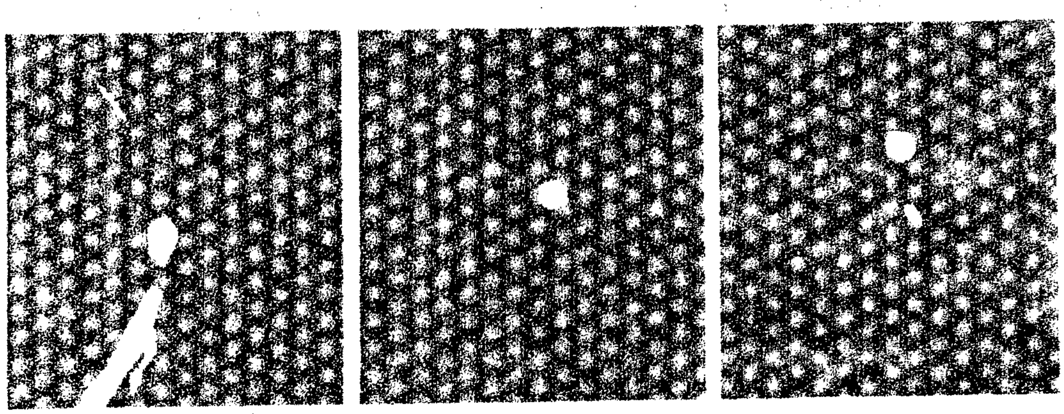

Figure 2. H = 1,500 oersteds, E = 1,850 volts/centimeter, V_0 = 40 kilovolts, PD_2 = 0.04 millimeters of mercury. Two photographs with different directions of the magnetic field; 7 pulsed discharges; D^+ -- parabola opening upward; D^- -- parabola opening downward; H^+ -- parabola opening upward (weak blackening)

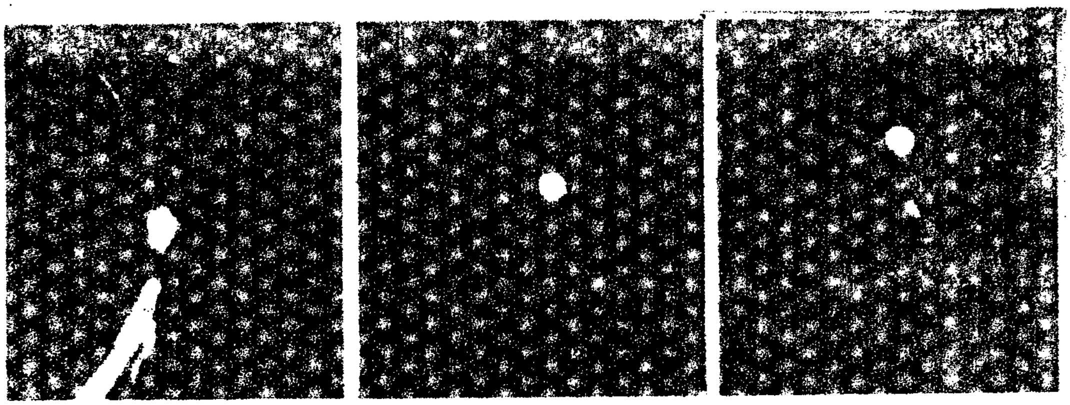

Figure 3. $H = 900$ oersteds, $E = 950$ volts/centimeter, $V_o = 38$ kilovolts, $PD_2 = 0.05$ millimeters of mercury. One pulsed discharge; D^+ -- parabola opening downward; H^+ -- parabola opening downward

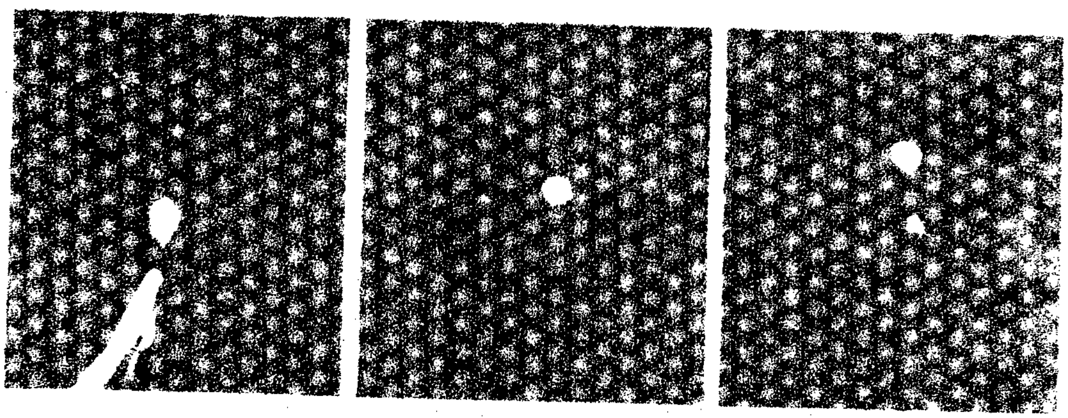

Figure 4. $H = 900$ oersteds, $E = 950$ volts/centimeter, $V_o = 40$ kilovolts, $PH_2 = 0.045$ millimeters of mercury; 12 pulsed discharges; H^+ -- parabola opening downward; H^- -- parabola opening upward

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